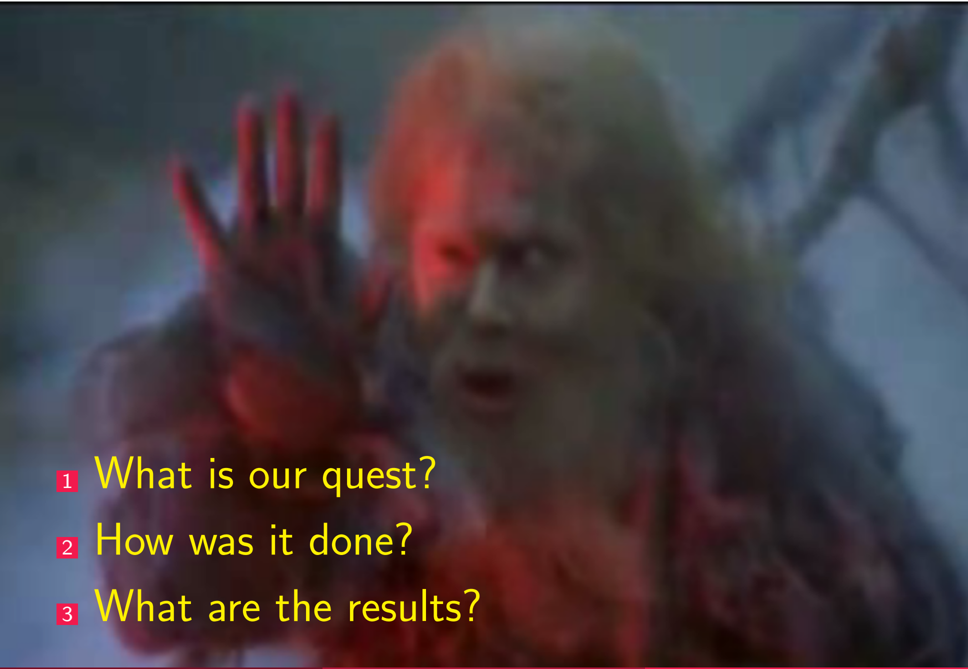
Final results on $K^+ \to \pi^+\nu\bar{\nu}$ from AGS E949

D. Jaffe August 12, 2008

Physics Department

BROOKHAVEN NATIONAL LABORATORY



1. What is our quest?
2. How was it done?
3. What are the results?

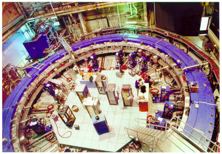
Our quest

Where does the Standard Model of particle physics break down?

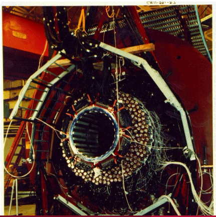
Two ways to look for "new physics":

Intensity frontier

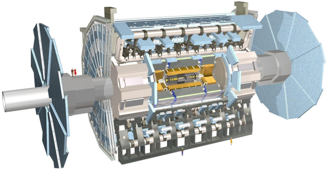
Precision measurements (muon g-2)



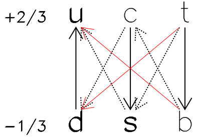
Rare decays ($K^+ \to \pi^+ \nu \bar{\nu}$)



Energy frontier (LHC)

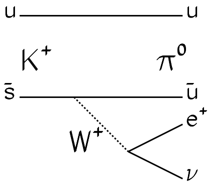


$K^+ \to \pi^+ \nu \bar{\nu}$ probes the basic constituents of matter

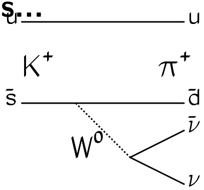


Heavy quarks decay to lighter quarks via the weak interaction

By the early 1970's...



Observed (5%)

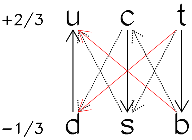


Not observed ($<10^{-6}$)

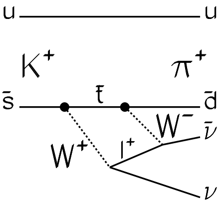
All observed flavor-changing decays also change electric charge

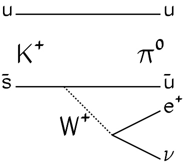
No evidence of flavor-changing neutral currents (FCNC) as predicted by theory of the time.

$K^+ \to \pi^+ \nu\bar{\nu}$ probes the basic constituents of matter



Third generation with $m_t >> m_c, m_u$ permits $K^+ \to \pi^+ \nu\bar{\nu}$ decay at second order.





Observed (5%)

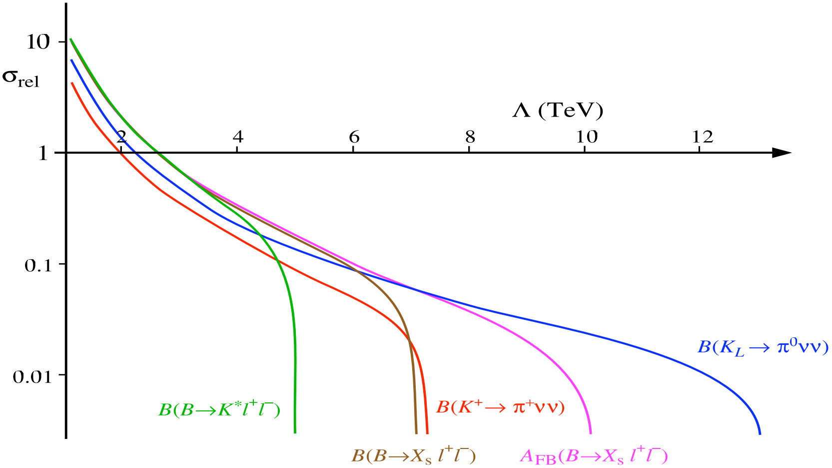
FCNC of $K^+ \to \pi^+ \nu\bar{\nu}$ in SM

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |V_{ts}^* V_{td}|^2$

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$

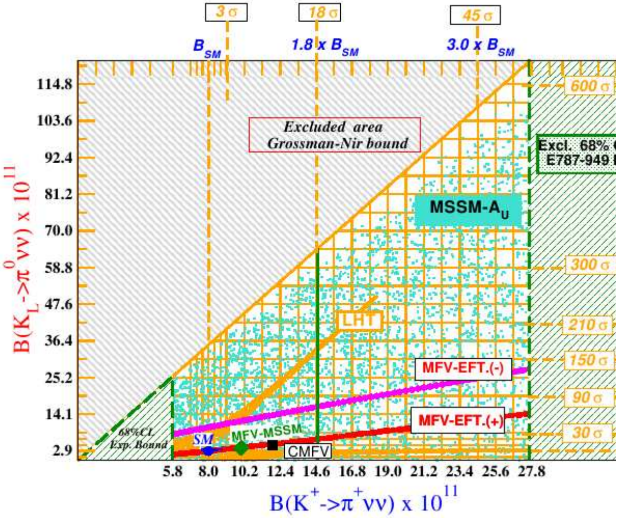
Strong interaction (QCD) part of $K^+ \to \pi^+ \nu\bar{\nu}$ decay is related by isospin to $K^+ \to \pi^0 e^+ \nu$ decay.

Sensitivity to New Physics



Ref: D.Bryman *et al.*, hep-ph/0505171

Sensitivity to New Physics



Ref: G.Isidori, arXiv:0801.3039

Experimental challenges of $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$

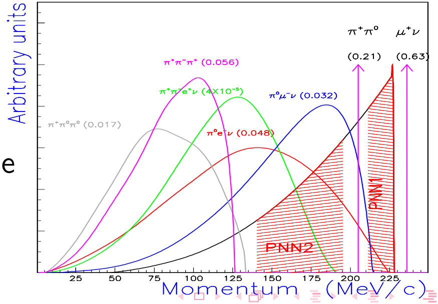
The decay $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ has a relatively weak experimental signature.

1. These is only one observable particle, the π^+, among the three particles in the final state because neutrinos interact too weakly to be observed.
2. The π^+ can be produced with a range of kinematically allowed values.
3. Only about 8 out of 100,000,000,000 K^+ is expected to decay to $\pi^+\nu\bar{\nu}$.

$K^+ \to \pi^+\nu\bar{\nu}$ can be observed

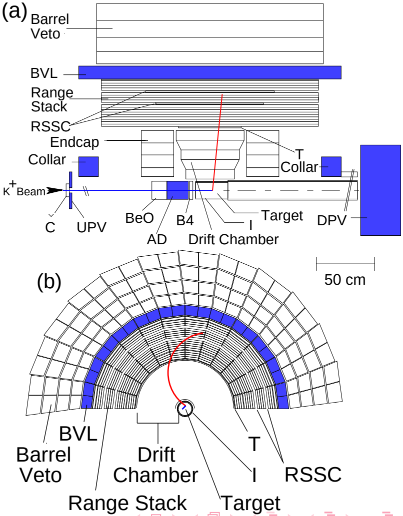
Region	**"PNN2"**	**"PNN1"**
$P(\pi^+)$ MeV/c	[140,195]	[211,229]
Stopped K^+	1.8×10^{12}	7.7×10^{12}
Background events	1.22 ± 0.24	0.45 ± 0.06
Candidate events	1	3
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$< 22 \times 10^{-10}$ (90% CL)	$(1.47^{+1.30}_{-0.89}) \times 10^{-10}$
Reference	PRD**70**, 037102 (2004)	PRD**77**, 052003 (2008)

Rate *vs.*
π^+ momentum in K^+ rest frame



E949 experimental method

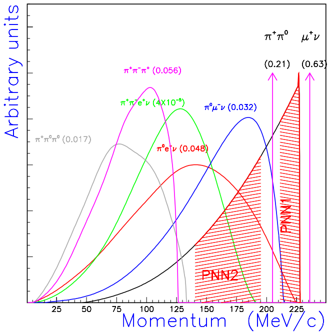
- **Measure everything possible**
- $\sim 700\ \mathrm{MeV}/c\ \mathrm{K}^+$ beam
- Stop K^+ in scint. fiber target
- Wait at least 2 ns for K^+ decay
- Measure P in drift chamber
- Measure range R and energy E in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in RS
- Veto photons, charged tracks
- New/upgraded detector elements compared to E787



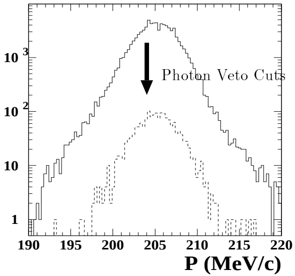
Backgrounds in high momentum (pnn1) region

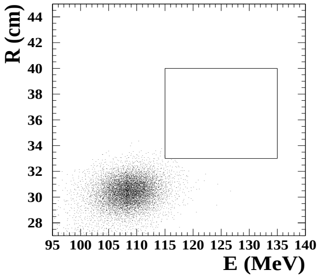
Mechanisms for the main backgrounds in the high momentum region

- $\mathrm{K}^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)
  1. Mismeasurement of π^+ kinematics
  2. Undetected photons from $\pi^0 \to \gamma\gamma$
- $\mathrm{K}^+ \to \mu^+\nu$ ($K_{\mu 2}$)
  1. Mismeasurement of μ^+ kinematics
  2. Misidentification of μ^+ as π^+



Example: Estimating $K^+ \to \pi^+\pi^0$ pnn1 background with data

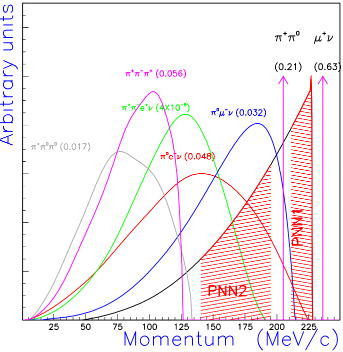




Left: Kinematically selected $K^+ \to \pi^+\pi^0$ with photon veto applied. Photon veto: Typically 2-5 ns time windows and 0.2 - 3 MeV energy thresholds

Right: Select photons. Phase space cuts in P, R, E.

Backgrounds in the pnn2 region



Process	Rate
$K^+ \to \pi^+\nu\bar{\nu}$	0.8×10^{-10}
$K^+ \to \pi^+\pi^0$	$2092000000.0 \times 10^{-10}$
$K^+ \to \pi^+\pi^0\gamma$	$2750000.0 \times 10^{-10}$
$K^+ \to \pi^+\pi^- e^+\nu$	409000.0×10^{-10}
$K^+ \to \mu^+\nu$	$6344000000.0 \times 10^{-10}$
$K^+ \to \mu^+\nu\gamma$	$62000000.0 \times 10^{-10}$
$K^+ \to \mu^+\pi^0\nu$	$332000000.0 \times 10^{-10}$
CEX	$\sim 46000.0 \times 10^{-10}$
Scattered π^+ beam	$\sim 25000000.0 \times 10^{-10}$

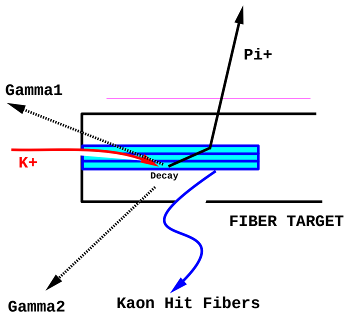
CEX $\equiv (K^+ n \to K^0 X) \times (K^0 \to K^0_L) \times (K^0_L \to \pi^+\ell^-\nu)$

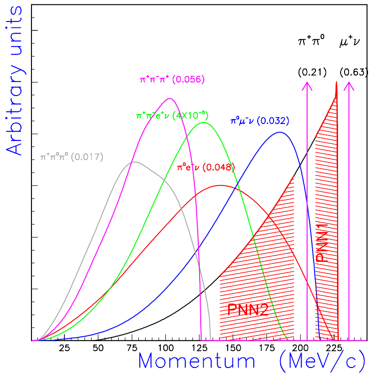
ℓ^- is μ^- or e^-

$K^+ n \to K^0 X$ rate is empirically determined.

Main pnn2 background: $K^+ \to \pi^+\pi^0$ -scatters

The main background below the $K^+ \to \pi^+\pi^0$ peak is due to $K_{\pi 2}$ decays where the π^+ scatters in the target losing energy and obscuring the correlation with the π^0 direction.

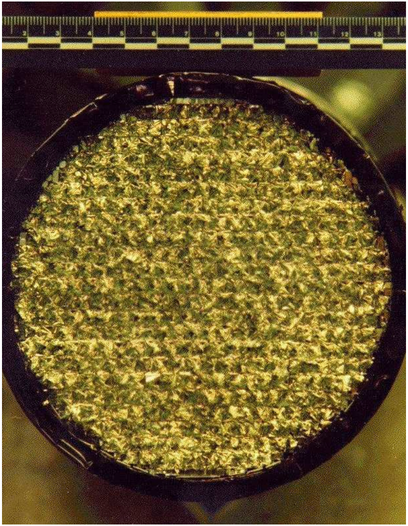


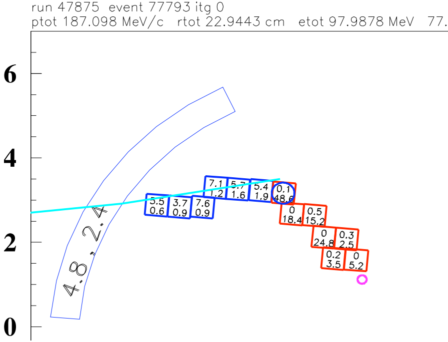


Suppression of $K_{\pi 2}$-scatter background

- Photon veto of $\pi^0 \to \gamma\gamma$
  Photon detection in beam region important
- Identification of π^+ scattering in the target
  - kink in the pattern of target fibers
  - π^+ track that does not point back to the K^+ decay point
  - energy deposits inconsistent with an outgoing π^+
  - unexpected energy deposit in the fibers traversed by the K^+

E949 scintillating fiber target



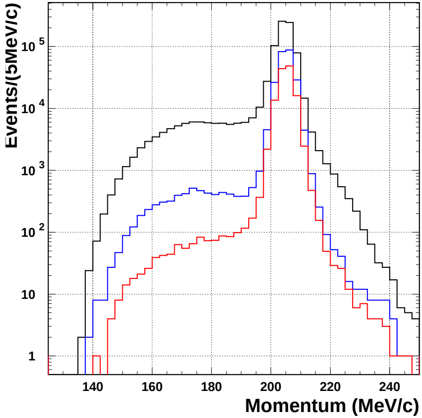


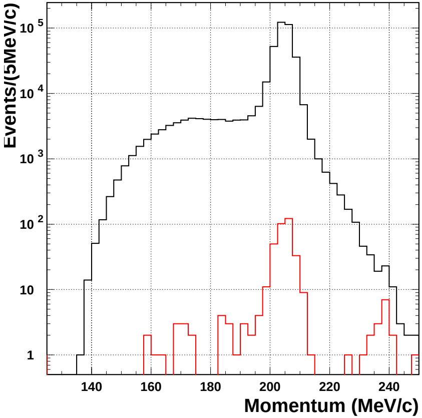
Identification of π^+ scattering

Kink

CCDPUL

Suppression of $K_{\pi 2}$ scatter background





Black: Inverted PV sample Blue: After target cuts (except CCDPUL) Red: After all target cuts

Black: Inverted target cuts sample Red: After photon veto cuts

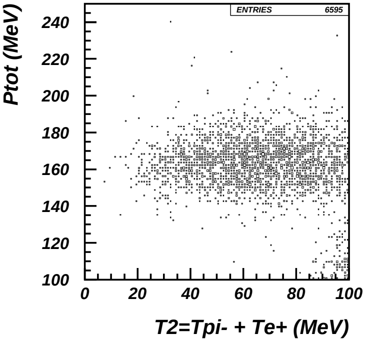
Estimation of $K_{\pi 2}$ scattering background

- $K_{\pi 2}$ scattering background is suppressed by PV and target cuts.
- To estimate PV rejection, multiple π^+ scattering samples are prepared by inverting different combinations of target cuts.
- The "normalization" sample is estimated by inverting the PV cut, but the sample is contaminated with $K_{\pi 2}$ scatters in the range stack (RS) and by $\mathrm{K}^+ \to \pi^+\pi^0\gamma$.

After disentangling the processes:

Process	Background events
$K_{\pi 2}$ TG-scatter	$0.619 \pm 0.150^{+0.067}_{-0.100}$
$K_{\pi 2}$ RS-scatter	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$

$\mathrm{K}^+ \to \pi^+\pi^- e^+\nu$ (K_{e4}) background

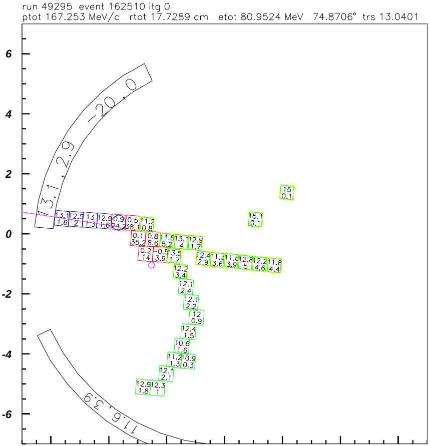


K_{e4} can be a background if the π^- and e^+ have very little kinetic energy and evade detection.

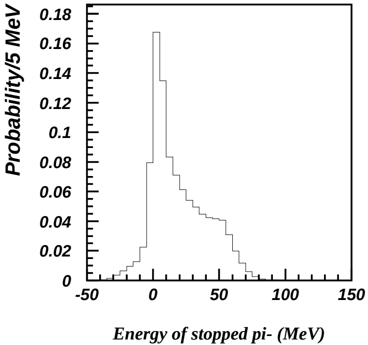
Figure: π^+ momentum *vs.* total kinetic energy of π^- and e^+ from simulated $\mathrm{K}^+ \to \pi^+\pi^- e^+\nu$ decays.

$K^+ \rightarrow \pi^+\pi^-e^+\nu$ background

Isolate K_{e4} sample using target pattern recognition, similar to $K_{\pi 2}$ scatter.



Estimate rejection power of target pattern recognition with simulated data supplemented by measured π^- energy deposition spectrum in scintillator.



Charge-exchange (CEX) background

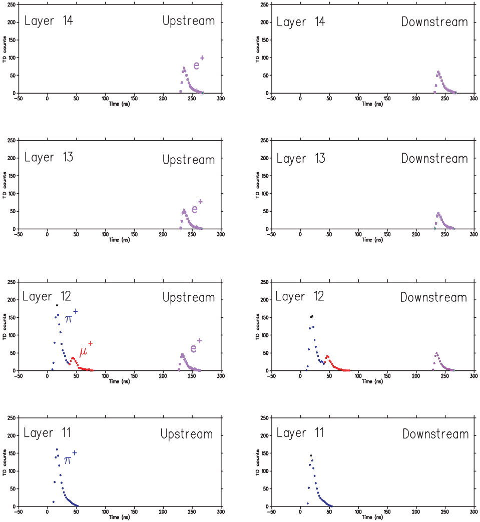
Mainly due to $(\mathrm{K}^{+} n \rightarrow \mathrm{K}^{0} X) \times$ $(\mathrm{K}^{0} \rightarrow \mathrm{K}_{\mathrm{L}}^{0}) \times (\mathrm{K}_{\mathrm{L}}^{0} \rightarrow \pi^{+} \ell^{-} \nu)$ where ℓ^{-} is μ^{-} or e^{-}.

Use measured $\mathrm{K}_{\mathrm{S}}^{0}$ events as input to simulation.

The delayed coincidence (DC) cut, $t_{\mathrm{K}} - t_{\pi} > 3$ ns, provides suppression because the $\mathrm{K}_{\mathrm{L}}^{0}$ decay must decay in the fiducial region ($\sim$20 cm) of the target.

Additional suppression provided by detection of the lepton.

Muon background



- Previous pnn2 analyses in E787 showed that muon background $(\mathrm{K}^+ \to \mu^+\nu\ , \mu^+\nu\gamma\ , \mu^+\pi^0\nu)$ was expected to be very small $(0.016 \pm 0.011$ events).
- Relax criteria on identification of $\pi^+ \to \mu^+ \to e^+$ decay chain to gain acceptance

Total background estimate

Process	Bkgd events (E949)	Bkgd events (E787)
$K_{\pi 2}$-scatter	$0.649 \pm 0.150^{+0.067}_{-0.100}$	1.030 ± 0.230
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$	0.033 ± 0.004
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$	0.052 ± 0.041
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$	0.024 ± 0.017
Muon	0.011 ± 0.011	0.016 ± 0.011
Beam	0.001 ± 0.001	0.066 ± 0.045
Total	$0.93 \pm 0.17^{+0.32}_{-0.24}$	1.22 ± 0.24
Total Kaons	1.70×10^{12}	1.73×10^{12}
Total Acceptance	1.37×10^{-3}	0.84×10^{-3}
SES	4.3×10^{-10}	6.9×10^{-10}

The branching fraction that corresponds to one event in the absence of background is the Single-Event Sensitivity (SES). For the E787+E949 pnn1 analysis, SES $= 0.63 \times 10^{-10}$.

Validation of background estimates

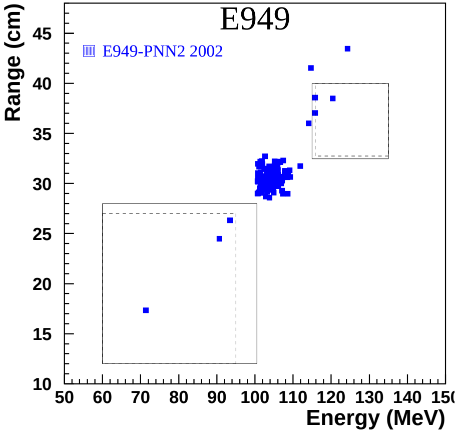
Relax PV and CCDPUL cuts to define 2 distinct regions PV_1 and $CCDPUL_2$ immediately adjacent to the signal region. Define a third region PV_2 by further loosening of the PV cut.

Region	N_{exp}	N_{obs}	$\mathcal{P}(N_{\mathrm{obs}}; N_{\mathrm{exp}})$	Combined
CCD_1	$0.79 \pm 0.35^{+0.30}_{-0.37}$	0	0.452 (0.652)	NA
PV_1	$9.09 \pm 0.65^{+1.38}_{-1.15}$	3	0.020 (0.044)	0.051 (0.130)
PV_2	$32.4 \pm 1.9^{+12.2}_{-7.9}$	34	0.613 (0.973)	0.140 (0.390)

Division of the signal region

- The background is not uniformly distributed in the signal region.
- Use the remaining rejection power of PV, DC, $\pi \to \mu \to e$ and KIN cuts to divide the signal region into 9 cells with differing levels of signal acceptance (s_i) and background (b_i).
- Calculate $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$ using s_i/b_i of any cells containing candidates using the likelihood ratio method.
- This procedure increases the total size of the signal region to increase acceptance at the cost of more total background.

Examining the signal region

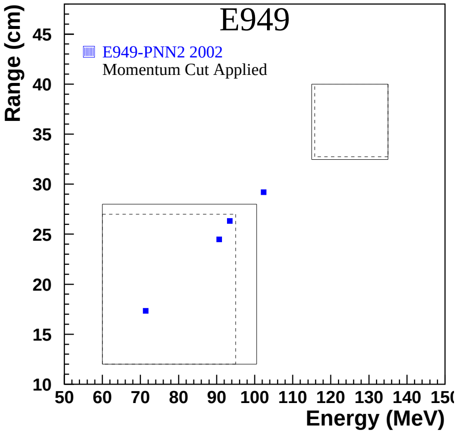


The nine cells

Bkgd	Cands	S/B
0.152	0	0.84
0.038	0	0.78
0.019	0	0.66
0.005	0	0.57
0.243	1	0.47
0.059	0	0.45
0.027	1	0.42
0.007	0	0.35
0.379	1	0.20

No momentum cut applied.

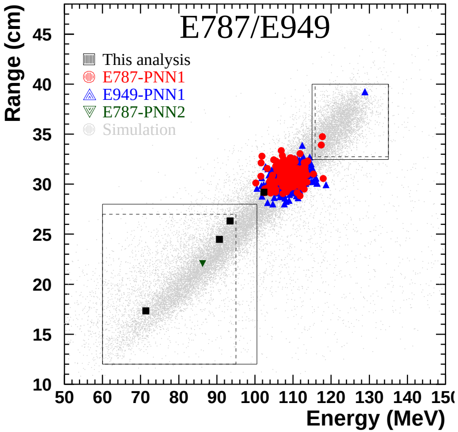
Measured $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ for this analysis



- $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (7.89^{+9.26}_{-5.10}) \times 10^{-10}$
- The probability of all 3 candidates to be due to background only is 0.037.
- SM expectation: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$

Momentum cut applied.

Measured $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ for E949+E787



Momentum cut applied.

- $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$
- The probability of all 3 candidates to be due to background only is 0.001.
- SM expectation: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$

How it began

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

DATE: October 17, 1983

TO: T. Kycia, S. Smith

FROM: R.B. Palmer

SUBJECT: E787

I have good news. Proposal 787, "Study of the Decay $K^+ \to \pi^+\nu\bar{\nu}$", has been approved for the full requested time of 2500 hours. The High Energy Advisory Committee strongly endorsed this proposal, characterizing it as dealing with one of the two most important areas in particle physics today;

E787 and E949 collaborators

$>$ xx physicists, xx institutes from Canada, China, Japan, Russia and the US.

A.J.S. Smith, A.J. Stevens, A.N. Khotjantsev, A.O. Bazarko, A.P. Ivashkin, A.P. Kozhevnikov, A.S. Turcot, A.V. Artamonov,

A. Daviel, A. Konaka, A. Kushnirenko, A. Sambamurti, B. Bassalleck, B. Bhuyan, **B. Lewis**, B. Viren, C. Ng, C. Witzig,

D.A. Bryman, D.E. Jaffe, D.I. Patalakha, D.R. Marlow, D.V. Vavilov, D. Akerib, E.J. Ramberg, E.W. Blackmore, E. Garber,

F.C. Shoemaker, G. Redlinger, I-H. Chiang, **I.-A. Christidi**, J.-M. Poutissou, J.A. Macdonald, J.R. Stone, J.S. Frank,

J.S. Haggerty, J.V. Cresswell, J. Hu, **J. Ives**, J. Mildenberger, J. Roy, K.K. Li, K. Mizouchi, K. Omata, K. Shimada,

L.G. Landsberg, L.S. Littenberg, M. Miyajima, M.A. Selen, M.LeNoble, M.M. Khabibullin, M.V. Diwan, M. Ardebili, M. Burke,

M. Convery, M. Ito, M. Kobayashi, M. Kuriki, M. Nomachi, M. Rozon, N.V. Yershov, N. Muramatsu, O.V. Mineev,

P.C. Bergbusch, P.D. Meyers, P.S. Cooper, P. Kitching, P. Padley, R.C. Strand, R.Soluk, R. McPherson, R. Poutissou,

R. Tschirhart, S.H. Kettell, S.V. Petrenko, S. Adler, S. Chen, S. Daviel, S. Kabe, S. Ng, S. Sugimoto, T.F. Kycia,

T.K. Komatsubara, T. Fujiwara, T. Inagaki, T. Nakano, T. Nomura, T. Numao, T. Sasaki, T. Sato, T. Sekiguchi,

T. Shimoyama, T. Shinkawa, T. Tsunemi, T. Yoshioka, V.A. Mukhin, V.F. Obraztsov, V.V. Anisimovsky, V. Jain, W.Sands,

Y. Kishi, Y. Kuno, Y. Tamagawa, Y. Yoshimura, Yi Zhao, Yu.G. Kudenko, and Zhe Wang

What happens next?

- In one of many ill-considered decisions of the Executive Branch of the US Government, E949 was cancelled in 2002 after receiving only 20% of the approved beam time.
- Experiment NA62 (formerly NA48/3) at CERN was approved in 2007 and is in preparation.
- NA62 proposes to observe $\approx$65 $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ per year with a background of $\approx$10 events using a 75 GeV/c beam. The use of kaon decay-in-flight to measure $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ has not been attempted before.
- There is a proposal to perform a stopped kaon decay experiment in Japan.

The last slide

- The results presented here are the culmination of 25 years of research with experiments E787 and E949 at the AGS.
- The measurement of the $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ branching ratio went from a limit of $< 1.4 \times 10^{-7}$ (90%CL)† to a measurement of $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ that is twice as large as, but still consistent with, the SM expectation of $(0.85 \pm 0.07) \times 10^{-10}$.
- The techniques, philosophy and results for E949 and E787 have shown the way for experimental searches of rare decays.

†Phys.Lett.B**107**, 159 (1981).